High-Resolution Wind Field Mapping in Support of the ONR Coupled Boundary Layer Air-Sea Transfer (CBLAST) Program

Donald R. Thompson
Johns Hopkins University/APL
Johns Hopkins Road
Laurel, MD 20723
phone: (240) 228-4559 fax: (240) 228-5548 email: donald_thompson@jhuapl.edu

Francis M. Monaldo
Johns Hopkins University/APL
Johns Hopkins Road
Laurel, MD 20723
phone: 240-228-8648 fax: 240-228-5548 email: frank_monaldo@jhuapl.edu

Nathaniel S. Winstead
Johns Hopkins University/APL
Johns Hopkins Road
Laurel, MD 20723
phone: 240-228-6152 fax: 240-228-5548 email: nathaniel.winstead@jhuapl.edu

Award #: N00014-01-1-0054
http://fermi.jhuapl.edu/CBLAST

LONG-TERM GOALS

The long-term goal of this research effort is to investigate the possibility of obtaining quantitative information about the near-surface wind field and perhaps other parameters that characterize the Marine Atmospheric Boundary Layer (MABL) from an analysis of Synthetic Aperture Radar (SAR) imagery. Because of its potential for yielding such information in the form of high-resolution imagery, this application of SAR, especially in coastal waters, would represent a significant advance over most scatterometer and passive microwave sensors that yield only coarse-resolution estimates of the wind field.

OBJECTIVES

Based on the results of effort over the past several years, we now believe that the possibility of generating high-resolution wind maps from SAR has been demonstrated. Our wind-map generation procedure has been automated so that high-resolution wind maps can be obtained from a SAR image within about 30 minutes after the raw image file is received at JHU/APL. The immediate objective of work on the present grant is to support the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer (CBLAST) Program field experiments by producing SAR wind maps over the experimental area south of Martha's Vineyard and with daily AVHRR sea-surface temperature (SST) imagery. This imagery provides valuable estimates of the spatial behavior of features near the air-sea interface. Furthermore, comparison between the SAR-derived wind predictions and *in situ* and airborne data collected during the CBLAST field experiments allows us to further refine our wind-mapping algorithms.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **High-Resolution Wind Field Mapping in Support of the ONR Coupled Boundary Layer Air-Sea Transfer (CBLAST) Program**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Johns Hopkins University/APL,,Johns Hopkins Road,,Laurel,,MD, 20723**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The long-term goal of this research effort is to investigate the possibility of obtaining quantitative information about the near-surface wind field and perhaps other parameters that characterize the Marine Atmospheric Boundary Layer (MABL) from an analysis of Synthetic Aperture Radar (SAR) imagery. Because of its potential for yielding such information in the form of high-resolution imagery, this application of SAR, especially in coastal waters, would represent a significant advance over most scatterometer and passive microwave sensors that yield only coarse-resolution estimates of the wind field.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

APPROACH

During the past year, we have converted eighteen standard-beam RADARSAT SAR images, collected during the CBLAST-low pilot experiment conducted in August 2002, into high-resolution wind speed maps. These wind maps have been made available to the other CBLAST researchers via the CBLAST web site (given below). For the 2003 main experiment, we have again ordered 23 standard beam RADARSAT SAR images and 18 EnviSAT alternating polarization images between July 25 and August 31, 2003. These latter alternating polarization images consist of interleaved VV- and HH-polarization data, and should be extremely useful in examining differences between C-band scattering at different polarizations. We also plan to assess the wind-mapping potential of each polarizations, and perhaps determine a more robust retrieval technique that utilizes a combination of both.

Of the 12 RADARSAT SAR images collected during the 2001 CBLAST pilot experiment, there were three overpasses when the NOAA LongEZ aircraft was concurrently collecting data. Two of these overpasses contained significant interference. (This interference was present in the processed SAR imagery received from ASF, and was not an artifact of our wind mapping procedure.) Using the uncontaminated image, we have nevertheless been able to make quantitative comparisons with the LongEZ data to further validate the SAR-derived wind fields.

WORK COMPLETED

- Comparison between wind maps derived from RADARSAT SAR imagery collected during the 2001 CBLAST pilot experiment and concurrent wind vector measurements from the NOAA LongEZ aircraft showed good agreement.
- Eighteen (of the requested 18) SAR overpasses from the standard beam mode (≈ 30 m resolution) of RADARSAT-1 collected over the CBLAST-low pilot experiment site south of Martha's Vineyard during August 2002 have been processed into wind maps and posted on our CBLAST web page at: http://fermi.jhuapl.edu/CBLAST/. Click "Overpasses; August 2002."
- Comparisons between the wind speeds estimated from these SAR wind maps show good agreement with the measurements from *in situ* sensors in the area.
- Twenty-three SAR overpasses from the standard beam mode of RADARSAT-1 and eighteen overpasses from the standard beam mode of EnviSAT (both at ≈ 30 m resolution) were ordered and collected between the dates of July 25 and August 31 2003 to support the 2003 CBLAST-low main experiment. Ten of the EnviSAT scenes have already been delivered to JHU/APL (as of 15 September 2003).
- We have presented recent results of our wind mapping work (including preliminary analysis of the EnviSAT alternation polarization mode imagery) at the "2nd Workshop on Coastal and Marine Applications of SAR" held at Svalbard Norway, 8-12 September, 2003.

LongEZ Track and Buoy Locations

Wind Speed Comparison

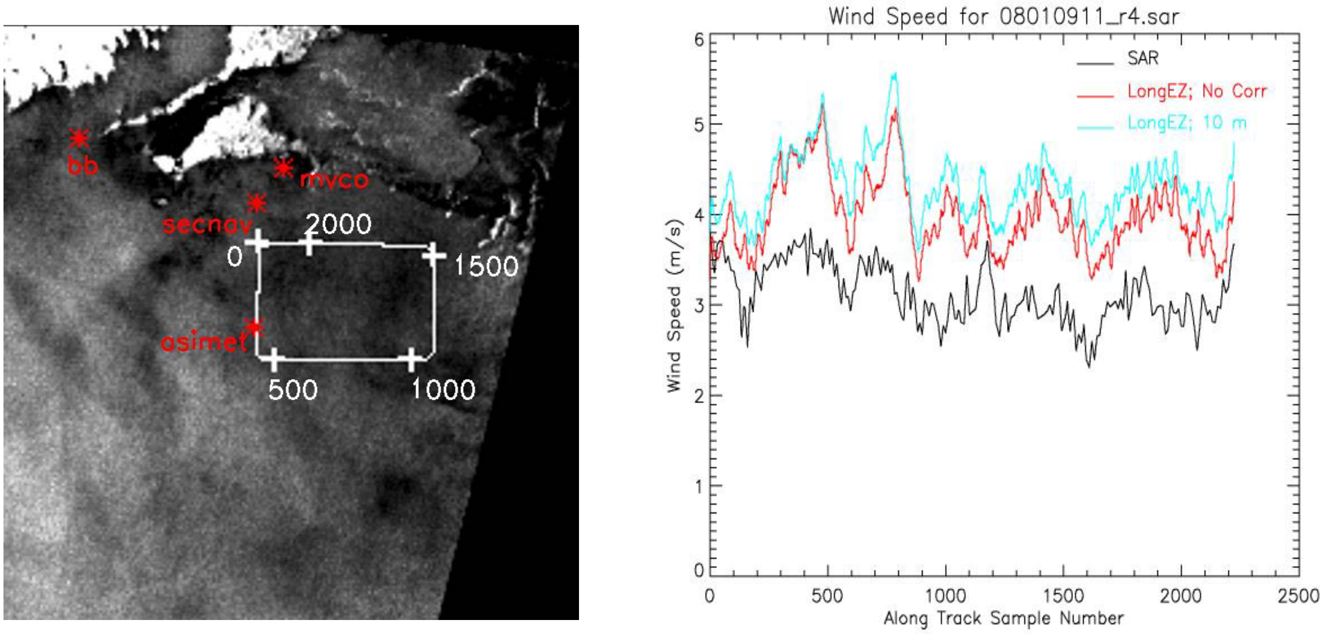

***Fig. 1:** (Left panel) Wind map of the CBLAST-low experimental area south of Martha's Vineyard on August 1, 2001 at 1058 UT created from a descending RADARSAT-1 overpass. The white line shows the LongEZ flight track at the SAR overpass time. The numbers along the track correspond to 1 s intervals. The red asterisks show the locations of 4 in situ wind sensors. (Right panel) Horizontal wind speed along the LongEZ flight track. The black curve shows the SAR-derived wind speed, the red curve shows the uncorrected LongEZ measurement, and the cyan curve shows the LongEZ measurement corrected to 10 m neutral stability.*

RESULTS

We have compared SAR wind maps from RADARSAT-1 imagery collected during the CBLAST-low pilot experiment, conducted in shelf waters off the south shore of Martha's Vineyard between mid July and mid August 2001 with winds measured on board the NOAA LongEZ aircraft during concurrent under flights. As discussed in last year's ONR progress report [*Thompson, et al.*; ONR, 2002], the overpasses coincident with the LongEZ flights contained significant interference due to a processing problem at the Alaska SAR Facility (ASF) during this time period. One of the overpasses (collected on August 1, 2001 at 1058 UT) was subsequently reprocessed by ASF to eliminate the interference. We have produced a surface wind map from this reprocessed image, and the portion of the map containing the concurrent LongEZ flight path is shown in the left hand panel of Fig. 1. The white line on the map marks the LongEZ flight path at the SAR overpass time and the numbers along this line are seconds from the zero mark (at the upper left corner of the rectangular track). The red asterisks on the map in the left-hand panel of Fig. 1 show the position of *in situ* wind measurements from the NOAA Buzzard's Bay buoy (bb), and three WHOI instruments. (Note that the position of the Martha's Vineyard Coastal Observatory, labeled mvco on the wind map, has been shifted into the ocean about 5 km south of its actual location on the south shore of Martha's Vineyard where the corresponding SAR wind speed was collected. More about this later.)

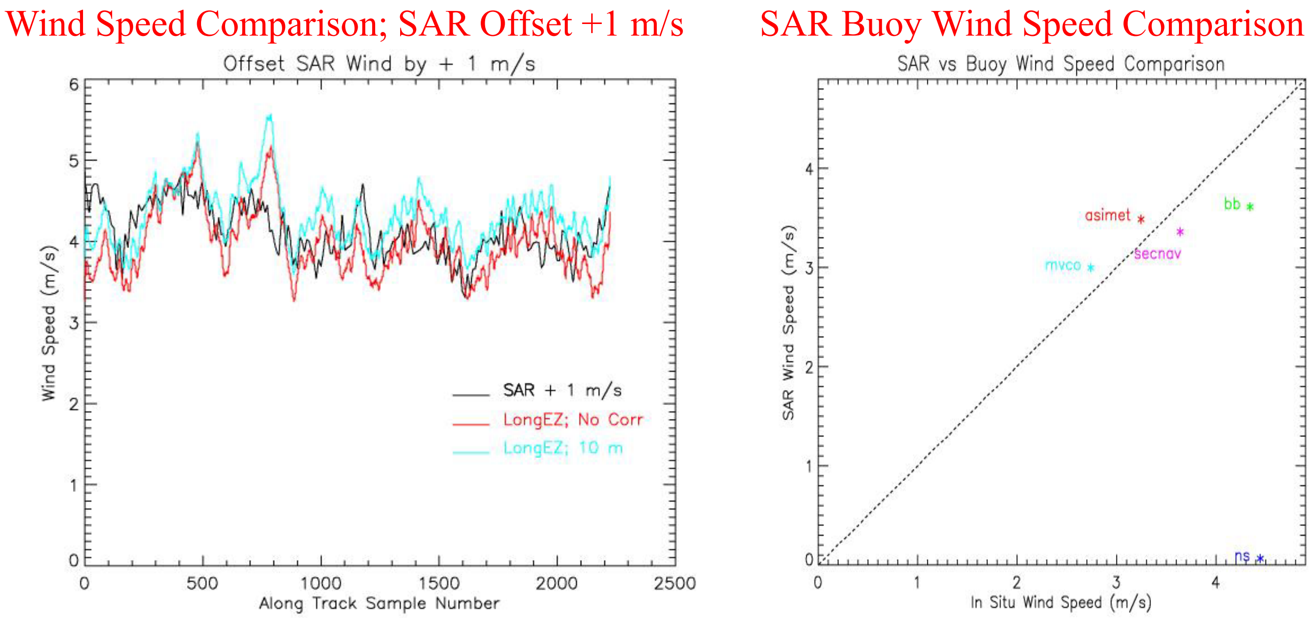

Fig. 2:** (Left panel) **Horizontal wind speed along the LongEZ flight track. The black curve shows the SAR-derived wind speed shifted higher by 1 m/s, the red curve shows the uncorrected LongEZ measurement, and the cyan curve shows the LongEZ measurement corrected to 10 m neutral stability.** (Right panel) **Comparison of SAR-derived wind speeds with wind speed measured at the 4 in situ buoys shown by the red asterisks in the left-hand panel of Fig. 1.

In the right-hand panel of Fig. 1, we compare the horizontal wind speed measured by the LongEZ with that extracted from the SAR wind map along the LongEZ flight line (shown in the left-hand panel). The black curve in the right-hand panel shows this SAR wind prediction. The red curve in this panel is the raw horizontal wind speed measured on board the LongEZ which was flying at altitude of roughly 10 m. the cyan curve shows this wind measurement corrected to 10 m neutral stability using the altitude and air-sea temperature difference measured aboard LongEZ and the Toga-Coare bulk flux algorithm [Fairall, et al., 1996].

One can see from the right-hand panel of Fig. 1 that although the SAR wind is biased about 1 m/s lower than the LongEZ measurement, the fluctuations about the mean wind from both sensors show quite close agreement. This agreement is seen more clearly in the left-hand panel of Fig. 2. This panel is the same as the right-hand panel of Fig. 1 except that the SAR-derived wind along the LongEZ flight track has been shifted higher by 1 m/s. We believe it is clear from this panel that the SAR and LongEZ were measuring basically the same wind field.

The right-hand panel of Fig. 2 show a comparison between the wind speed measured by the in situ buoys shown by the red asterisks in the left-hand panel of Fig 1 and that extracted from the SAR wind map. (Note that no bias has been added to the SAR-derived wind for this comparison.) One can see from this panel that the SAR-derived wind speed at the position of each of the four buoys is in good agreement with the speed measured by the wind sensor on the buoy itself.

Unfortunately, none of the remaining SAR images that coincide with LongEZ flight days during the CBLAST 2001 pilot experiment have been reprocessed by ASF. Clearly, more cases are needed. However, we believe that the comparisons presented above are quite encouraging, and clearly illustrate

the potential of the high-resolution SAR wind mapping technique. In fact, we believe these comparisons represent the first time that SAR wind estimates have been compared with more conventional measurements at comparable resolution. Furthermore, our present findings are quite consistent with the results of previous studies where comparisons of SAR-derived winds with those from NOAA buoys [Monaldo, et al., 2001] and QuikSCAT [Thompson, et al., 2001] show similar good agreement. In fact, it seems to us that high-resolution SAR wind maps may be the only available means to experimentally measure the spatial variability of the near surface wind field in the marine boundary layer. Because of this fact coupled with the relatively dense temporal coverage from RADARSAT and EnviSAT overpasses now available, SAR wind maps should provide important constraints on the modeling studies and analysis of data from the CBLAST main experiment carried out last summer.

IMPACT/APPLICATIONS

The operational need for high-resolution wind maps is urgent. The primary application users for the products and techniques produced by this work are government agencies tasked with coastal marine weather forecasting, natural resource protection and management as well as those charged with safety and law enforcement in coastal areas. There is now a strong consensus in the remote-sensing community that high-resolution winds can be measured using SAR. From a scientific standpoint, SAR-derived high-resolution wind maps provide the first opportunity to study the spatial variability of the surface wind field over an extended area at resolutions less than one kilometer. Knowledge of wind variability at these scales is important for understanding the effect of rapid changes in the surface boundary conditions, caused for example by sharp variations in the local topography or surface temperature, on the near-surface atmospheric circulation. It seems to us that the high-resolution surface wind measurements possible with the SAR mapping technique should contribute greatly to meeting the objectives of the ONR CBLAST program.

TRANSITIONS

As part of the Alaska SAR Demonstration phase of the NOAA StormWatch Program, we have been supplying since 2000, SAR wind maps in near real time to meteorologists in Alaska as a forecasting aid in this topologically-complicated region. Plans are underway to set up a similar system to produce SAR wind maps along the US east coast in conjunction with the new CSTARS Facility at the University of Miami.

RELATED PROJECTS

NOAA/NESDIS is currently funding the applications-oriented portion of our SAR wind mapping effort under the auspices of ONR. In Europe, the integration and application of SAR data is being prototyped as part of the Marine SAR Analysis and Interpretation System (MARSAIS). [*Johannessen et al.,* 2001] as a joint project led by the Nansen Environmental and Remote Sensing Center in Norway. The goal of MARSAIS is to produce products (including high-resolution wind estimates) and tools to permit the more effective utilization of SAR data in coastal areas.

REFERENCES

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young, “Bulk parameterization of air-sea fluxes for the Tropical Ocean Global-Atmosphere Coupled-Ocean Atmosphere Response Experiment,” *J. Geophys. Res., 101 C2*, 3747-3764, 1996.

Johannessen, J. A., R. Garello, B. Chapron, R. Romeiser, P. Pavlakis, I. Robinson, N. Connolly, K. Nittis, T. Hamre, S. Ufermann, W. Alpers, H. Espedal, B. R. Furevik, V. Cummins, D. Tarchi, Marine SAR analysis and interpretation system — MARSAIS, *Annales de Telecommunications, 56,* 655–660, 2001.

Monaldo, F. M., D. R. Thompson, R. C. Beal, W. G. Pichel, and P. Clemente-Colón, “Comparison of SAR-derived wind speed with model predictions and ocean buoy measurements,” *IEEE Trans. Geosci. Remote Sensing, 39*, 2587-2600, 2001.

Thompson, D. R., F. M. Monaldo, N. S. Winstead, W. G. Pichel, and P. Clemente-Colón, “Using Combined SAR and Scatterometer Estimates for Improved High-Resolution Coastal Wind Mapping,” *Eos, 82*, 469-474, October 9,2001.

Thompson, D. R., F. M. Monaldo, and N. S. Winstead, “High-Resolution Wind Field Mapping in Support of the ONR Coupled Boundary Layer Air-Sea Transfer (CBLAST) Program,” *ONR Ocean, Atmosphere, and Space, Fiscal Year 2002 Annual Reports (Revised Edition),* CD-Rom, June 2003.

PUBLICATIONS

Babin, S. M., T. D. Sikora and N. S. Winstead, “A case study of satellite-derived synthetic aperture radar signatures of spatially evolving atmospheric convection over the Western Atlantic Ocean,” *Boundary Layer Meteorology*, 106, 527-546, 2003, [Published, Refereed].

Barnum, B. H., N. S. Winstead**,** J. Wesly, Lt. A. Hakola, P. R. Colarco, O. B. Toon, P. Ginoux, G. Brooks, L. Hasselbarth, and B. Toth: “Forecasting dust storms using the CARMA-dust model and MM5 Weather Data.” *Environmental Modeling and Simulation*, [In Press, Refereed]

Elfouhaily, Tanos, Stephan Guignard, Ra'id Awadallah, and Donald R Thompson, “Local and non-local curvature approximation: A new asymptotic theory for wave scattering,” *Waves in Random Media*, [In Press, Refereed].

Elfouhaily, Tanos, Stéphan Guignard, and Donald R. Thompson, “Formal tilt invariance of the local curvature approximation,” *Waves in Random Media*, *13-4*, L7-L11, 2003, [Published, Refereed].

Elfouhaily, Tanos, Stéphan Guignard, and Donald R. Thompson, “A practical second-order electromagnetic model in the quasi-specular regime based on the curvature of a 'good-conducting' scattering surface,” *Waves in Random Media*, *13-3*, L1-L6, 2003, [Published, Refereed].

Elfouhaily, Tanos, Maminirina Joelson, Stéphan Guignard, and Donald R. Thompson, “Analytical comparison between the surface current integral equation and the second-order small-slope approximation, *Waves in Random Media*, *13-3*, 165-176, 2003, [Published, Refereed].

Elfouhaily, Tanos, Maminirina Joelson, Stéphan Guignard, Hubert Branger, Donald R. Thompson, Bertrand Chapron, and Douglas Vandemark, “Analysis of random nonlinear water waves: The Stokes-Woodward technique,” *C. R. Mecanique 331*, 189-196, 2003, [Published, Refereed].

Horstmann, J., W. Koch, N. Winstead, F. Monaldo, D. Thompson, P. Clemente-Colón and W. Pichel “Comparison of RADARSAT-1 SAR Retrieved Wind Fields to Numerical Models,” IGARSS 2003, *IEEE* CD-ROM, Toulouse, France, July 21-25, 2003, [Published].

Monaldo, F. M., D. R. Thompson, W. G. Pichel, and P. Clemente-Colón, “A Systematic Comparison QuikScat and SAR measured wind speeds,” *IEEE Trans. Geosci. Remote Sensing,* [In Press, Refereed].

Monaldo, Frank, “SAR Wind Speed Retrieval,” book chapter in *NOAA SAR Users Manual*, editors: J. Apel and C. Jackson, [In press, Refereed]

Monaldo, Frank, Donald Thompson, Nathaniel Winstead, “Combining SAR and Scatterometer Data to Improve High Resolution Wind Speed Retrievals,” IGARSS 2003, *IEEE* CD-ROM, Toulouse, France, July 21-25, 2003, [Published].

Sikora, T. D., G. S. Young, R. C. Beal, F. M. Monaldo, P. W. Vachon, and N. S. Winstead, “Applications of synthetic aperture radar in marine meteorology,” book chapter in *Atmosphere Ocean Interactions*, editor: W. Perrie, Series in *Advances in Fluid Mechanics*, [submitted].

Thompson, Donald R., “Microwave Scattering from the Sea,” book chapter in *NOAA SAR Users Manual*, editors: J. Apel and C. Jackson, [In press, Refereed]

Thompson, Donald R., Lloyd A. Linstrom, Richard F. Gasparovic, and Tanos M. Elfouhaily, “Doppler Analysis of GPS Reflections from the Ocean Surface,” IGARSS 2003, *IEEE* CD-ROM, Toulouse, France, July 21-25, 2003, [Published].

HONORS/AWARDS/PRIZES

Donald R. Thompson, Johns Hopkins University/APL, Adjunct Professor, Rosenstiel School of Marine and Atmospheric Science, University of Miami.

Francis M. Monaldo, Johns Hopkins University/APL, Chairman, Wind Applications Session, “2nd Workshop on Coastal and Marine Applications of SAR,” Svalbard Norway, 8-12 September 2003.

Donald R. Thompson, Johns Hopkins University/APL, Scientific Committee, “2nd Workshop on Coastal and Marine Applications of SAR,” Svalbard Norway, 8-12 September 2003.